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Modal evolution of induced second-harmonic light in an optical fiber

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We show how the mode of the photoinduced second-harmonic light in an optical fiber changes with preparation time. We also discuss what type of nonlinear interaction can be causing the induced second-harmonic light and give experimental evidence that the initial second-harmonic light is a core–cladding interface effect.

Several phenomena are connected with the surprising discovery of efficient second-harmonic (SH) generation in optical fibers. One is the change of mode as the SH light grows in the fiber.[1,2] In the literature one finds without exception that the initially generated SH light is always in an asymmetric mode [LP_{31} (Ref. 3) or LP_{11} (Ref. 4)]. However, the photoinduced SH light from a photoprepared fiber seemingly appears randomly in both symmetric and asymmetric modes.[1,2] Since the particular mode in which the SH light propagates is a clue to what nonlinear interaction is causing it, in this Letter we describe some of the parameters that affect the modal evolution of the photoinduced or growing SH light in an optical fiber. In addition, we have also studied the influence of germanium and the difference in refractive index between the core and the cladding on the efficiency of the initial SH light, which, it has been argued, arises from electric-quadrupole-type interactions.[4,5] However, so far it has not been clearly determined from where within the fiber the SH light is generated. In this Letter we show from experimental observations that the initially quadrupole-generated SH light has its origin in the core–cladding interface.

A mode-locked and Q-switched Nd:YAG laser was used to excite the fibers. The length of fibers used was approximately 5–7 cm. The fibers used in these experiments were either pure-silica-core fibers or germanium-doped fibers with a Δn between the core and cladding of 0.008 or 0.017, respectively. The reason for using a fiber with a high Δn was to generate a sufficient amount of initial SH light to allow us to take a picture of it.

The suspicion that a large Δn would be important for generating large amounts of initial SH light was triggered by the theoretical calculations of Terhune and Weinberger,[5] which show that the core–cladding interface provided the largest overlap integral for the fundamental and SH modes. To verify the importance of the core–cladding interface experimentally we used three different types of optical fiber. Fiber A had a pure-silica core, a Δn of ~0.008, and a normalized frequency $V \sim 3.5$ at the fundamental wavelength; fiber B was doped with ~3 mol % GeO_2 in the core but had the same Δn and V as fiber A; and fiber C was heavily doped with GeO_2 in the core (~15.6 mol %), which resulted in a Δn of ~0.017 and $V \sim 2.49$. Both fibers A and B produced ~180-nW peak power of initial SH light when excited with ~10-kW peak-power pulses at the fundamental wavelength. This shows that the amount of initial SH light is independent of the GeO_2 concentration. In contrast, the high-Δn fiber produced ~5-mW peak-power pulses at the SH wavelength for the same input conditions as above, i.e., an increase of 4 orders of magnitude. Clearly the refractive-index step at the core–cladding interface exerts a strong influence on the amount of initial SH light generated in the fiber. It is also reasonable to attribute the origin of the initial SH light to a quadrupole interaction, phenomenologically described by $P_i = \Gamma_{ijkl} E_j \nabla_k E_l$. The reason is, of course, that the quadrupole interaction is sensitive to changes in the refractive-index step across the core–cladding interface owing to the gradient of the electric field. In interpreting these results we have taken into account that the magnitude of the overlap integral for the different fibers is proportional to Δn at the interface. Furthermore the output of SH intensity showed a variation of only ±10% between different pieces of fiber from the same type of fiber. It seems, therefore, that the oscillations in intensity of the non-phase-matched SH light are being washed out, stabilizing the output around an average value for fiber lengths much longer than the coherence length.[4]

The anomalous characteristic of SH generation in optical fibers is obviously the fact that the intrinsic SH light (explainable through nonlocal nonlinearities) does not stay constant but grows with time. Typically, as the SH light is growing, its mode changes. We have studied how this change in mode depends on the IR intensity used to prepare the fiber.

By placing a Nikon F3 camera with the lens removed directly after the fiber, it was possible to record the mode for the initial SH light by using fiber C

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(because of the large amount of initial SH light generated by this fiber). In Fig. 1 we show the mode pattern for vertical and horizontal polarizations of the SH light at the output end of the fiber for different preparation times. The input fundamental (preparation) light was vertically polarized. The first mode pattern is recorded at time $t = 0$ and the others at $t = 1$ h, $t = 1.5$ h, $t = 2$ h, and $t = 2.5$ h, with the output polarization indicated by the arrows in Fig. 1. The difference in spot size along the sequence of photographs is due to slight variations in the distance between the plane of the film and the fiber end that occurred every time the camera was removed to change film. Furthermore the same photograph was used for the vertical polarization for the last three preparation times since the mode pattern did not change. Each time the pictures were taken, the power of the SH light was recorded. The growth with time of the SH light for the same run as in Fig. 1 is shown in Fig. 2. One immediate observation is that the changes in the mode pattern for the vertical and horizontal polarizations do not appear at the same power levels. Another observation is that the ratio between the vertically and horizontally polarized SH light increases as the fiber is being prepared.

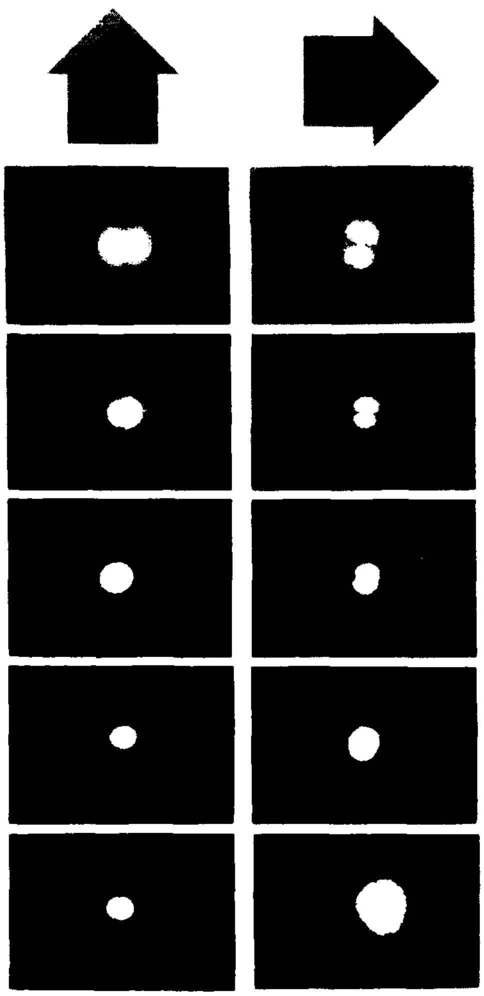

Fig. 1. Modal evolution of SH light ($\lambda = 0.532$ μm) in an optical glass fiber. The photographs for the vertical and horizontal polarizations were taken at (a) $t = 0$, (b) $t = 1$ h, (c) $t = 1.5$ h, (d) $t = 2$ h, and (e) $t = 2.5$ h.

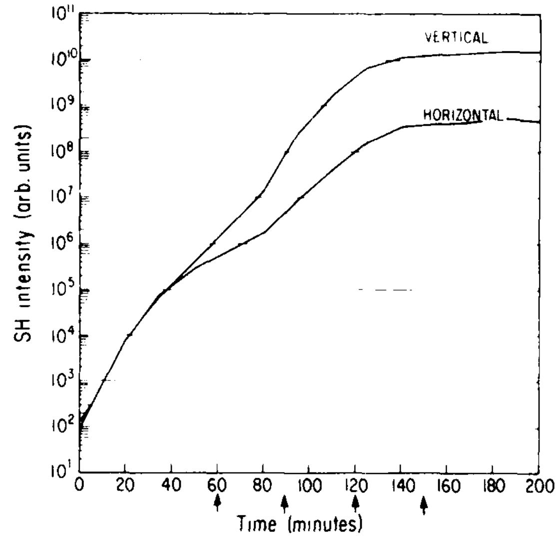

Fig. 2. Growth of the vertical and horizontal SH light with time in a 7-cm-long piece of optical fiber. The arrows along the time scale refer to when the different photographs were taken.

A systematic study of this ratio reveals that the ratio for the initial SH light is

$$\frac{\uparrow 2\omega}{\rightarrow 2\omega} = 2.4 \pm 1.2, \tag{1}$$

and that for the saturated photoinduced SH light is

$$\frac{\uparrow 2\omega}{\rightarrow 2\omega} = 30 \pm 10. \tag{2}$$

These ratios were found to be completely independent of the intensity and the polarization preservation of the fundamental light. For example, when the ratio between vertical and horizontal polarization of the fundamental (preparation) light was varied from 1000:1 to 10:1, the ratios (1) and (2) were still the same.

Although pieces of fiber C from the same drum were measured under identical conditions, there was a wide variation in polarization ratios. Contiguous fiber sections had similar ratios, but over lengths of 6–7 m as much as 2-order-of-magnitude variation could be measured. These extremely different polarization ratios are attributed to draw-induced geometrical variations. Since we measured many different pieces of fiber to determine the SH polarization ratio with statistical significance, we also were able to study the influence of the polarization ratio of the fundamental (preparation) light on the induced polarization ratio of the SH light. The errors recorded were due not to different intensities or polarizations but to geometrical variations between fibers under identical experimental conditions.

Something that changed drastically with intensity, however, was the evolution of the mode pattern for the SH light. The sequence in Fig. 1 was recorded with low-power IR light ($\lambda = 1.064$ μm, $P_{peak} \sim 6$ kW). If the IR power used to prepare the fiber was increased to 10 kW or more, no change in the mode could be recorded. In other words, at high power the SH light stayed in the LP_{11} mode from start to finish. There existed a

small range of fundamental intensity for which the final (saturated) SH mode was in a mode intermediate between LP_{11} and LP_{01} [e.g., the mode for the vertical polarization after 1 h of preparation; Fig. 1(b)].

There are immediately two possibilities that come to mind to explain the change of mode for the SH light. The first is that the nonlinear susceptibility induced in the glass forces the growing SH light into one particular mode. The reason for this can be seen from the overlap integral f:

$$f = \frac{1}{N}\int_0^{\infty}\int_0^{2\pi} \mathbf{P}^{2\omega}(r, \theta) x \mathbf{H}^{2\omega}(r, \theta) r dr d\theta, \qquad (3)$$

where N is a normalization factor.[6]

Depending on the nonlinear polarization $\mathbf{P}(r, \theta)$, the angular part of integral (3) is zero for certain mode combinations. For example, it was shown in Ref. 5 that an electrical-quadrupole interaction could generate SH light only in asymmetric modes (LP_{11}, LP_{21}, LP_{31}, etc.) if both fundamental photons were launched into the LP_{01} mode. This would mean that the induced SH light could not be from an electric-quadrupole interaction since it appears in both symmetric and asymmetric modes (for an IR input with both photons in the LP_{01} mode). However, the observation of symmetric–asymmetric modes for the induced SH light in principle rules out an electric-dipole interaction, too, unless (as was suggested by Kashyap[3]) we induce an electric-dipole nonlinear susceptibility with an angular dependence that, when inserted into Eq. (3), gives a nonzero overlap integral for both symmetric and asymmetric modes for the SH light. In this case the change of mode during preparation could be caused by a change of the underlying nonlinear interaction.

A second possibility is that a change of the refractive index is taking place during the preparation process, which causes mode coupling. For fiber C, which was exclusively used for the modal evolution studies, the difference in refractive index between the LP_{11} and LP_{01} modes in the green is $\sim 5 \times 10^{-3}$. We propose that an induced change in refractive index would be proportional to the laser energy, in accordance with the studies of Hill *et al.*[7] Such an effect could explain why the mode changes for the long preparation times (low IR intensities) but not for the short preparation times (high IR intensities). A question that comes to mind then is whether the mode pattern will change in the case of high-intensity, short preparation times after the SH light has saturated. The answer from experiments that we performed is no. A final observation, mentioned above, that argues against a refractive-index change as the cause of the modal change for the SH light is that the vertical and horizontal modes change at different energies (see Fig. 2). In other words, it seems likely that the modal changes that occur in the growing SH light are due to changes in the nonlinear interaction causing the SH light. This assumption does not rule out the possibility of changes in the refractive index during the preparation but indicates that the magnitude of these changes is not large enough for mode coupling to occur.

In conclusion, we have shown that the mode structure of photoinduced SH light in optical fibers is a function of the IR intensity used to create it. We have also argued from experimental observations that the changes in the mode of the SH light are due to a change in the underlying nonlinear interaction creating the SH light and not from changes in the refractive index. We have also given experimental evidence that the intrinsic SH light is generated at the core–cladding interface. Finally, we showed that the ratio between the vertical and horizontal polarization of the induced SH light is of a fundamental character and is independent of the intensity and the ratio between vertical and horizontal polarizations of the fundamental light.

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